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100-Gbps RZ Data Reception in 67-GHz Si-Contacted Germanium Waveguide p-i-n Photodetectors

Hongtao Chen, M. Galili, P. Verheyen, P. De Heyn, G. Lepage, J. De Coster, S. Balakrishnan, P. Absil, L. Oxenlowe, J. Van Campenhout, and G. Roelkens

(Top Scored)

***Abstract*—We demonstrate 100-Gbps silicon-contacted germanium waveguide p-i-n photodetectors integrated on imec's silicon photonics platform. The performance of 14 and 20 μm long devices is compared. The responsivity of the devices is 0.74 and 0.92 A/W at 1550 nm, respectively.**

***Index Terms*—Germanium, integrated optoelectronics, optical communications, photodetectors.**

I. Introduction

Advanced optical receivers require photodetectors with high opto-electrical bandwidth, high responsivity and low dark current. Germanium waveguide p-i-n photodetectors have been studied extensively for this purpose as they can be realized on silicon photonic integrated circuits [1]–[13]. Conventional Ge p-i-n photodetectors require a metal contact on Ge to form the p-i-n junction. As the process to form a metal contact to Ge is less well developed, the high contact resistance at the metal/Ge interface [14] contributes to a large RC-constant, which normally determines the opto-electrical bandwidth of the Ge p-i-n photodetector. This limits the performance of Ge p-i-n photodetectors in high-speed optical communication systems. 100 Gbps data reception using Ge photodetectors has therefore not been demonstrated before.

We demonstrated a Ge p-i-n photodetector without metal contacts on Ge, grown on and contacted through a silicon p-i-n diode structure, adopting a 400 nm thick Ge layer (referred to as Si-LPIN GePD hereafter) [11]. The opto-electrical 3-dB bandwidth was transit-time limited to 20 GHz at -1 V bias at 1550 nm. Removing the metal contacts on Ge significantly enhances the responsivity as light absorption from the metal contacts is responsible for a substantial responsivity loss. The measured responsivity at -1.2 V bias was over 1 A/W across the whole C-band. In addition, the device showed a very low dark current of 3 nA at -1 V.

In [15], [16] we demonstrated that by adopting a 160 nm thick Ge layer to reduce the transit time, the opto-electrical 3-dB bandwidth at -1 V bias was enhanced to 67 GHz at 1550 nm for a 14 μm long Si-LPIN GePD. The junction capacitance was 6.8 fF at -1 V. Light coupling from the silicon-on-insulator (SOI) waveguide to the Ge waveguide was optimized by adding a poly-Si taper on top of the fully etched Si taper as shown in Fig. 1(a). The measured responsivity at -1 V bias was 0.74 A/W at 1550 nm. The dark current was as low as 4 nA at

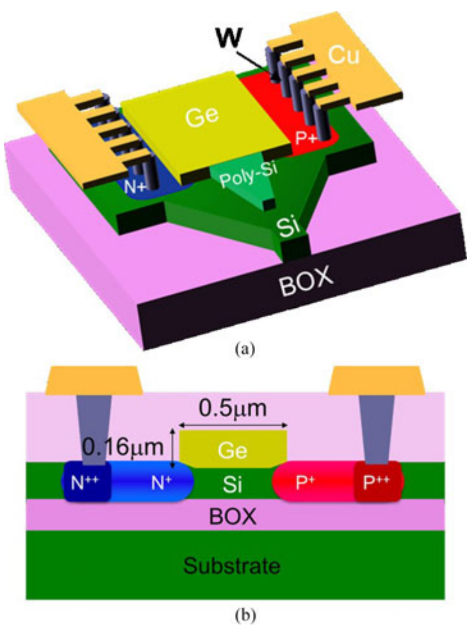

Fig. 1. (a) 3-D schematic of the Si-LPIN GePD. The poly-Si taper is 120 nm thick, with a width varying from 150 nm to 250 nm over a length of 20 μm, and the single-mode Si waveguide is 450 nm wide. (b) Cross-section schematic of the Si-LPIN GePD with a 0.16 μm thick and 0.5 μm wide Ge layer.

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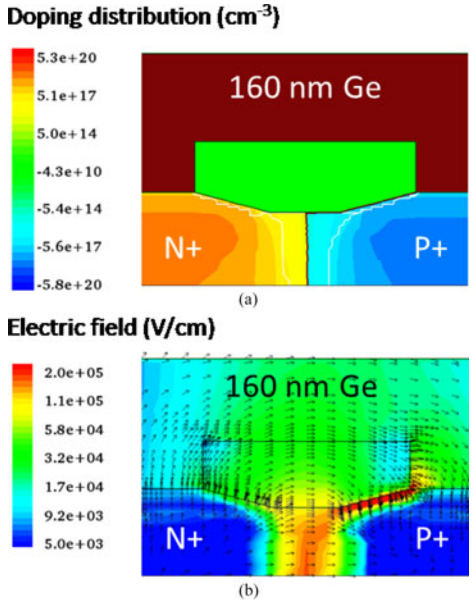


Fig. 2. (a) Simulated doping distribution in the Si-LPIN GePD using *Sentaurus Process*. (b) Simulated electric field distribution in the Si-LPIN GePD at –1 V bias using *Sentaurus Device*. The electric field direction is annotated in the graph.

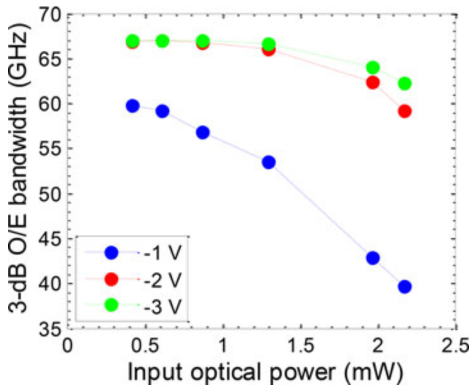


Fig. 3. 3-dB opto-electrical bandwidth as a function of input optical power at 1550 nm wavelength for the 14 μm long Si-LPIN GePD (reproduced with permission from [16]).

-1 V. 56 Gbps on-off keying non-return-to-zero data reception was demonstrated with clear open eye diagrams at 1550 nm at -1 V bias [16].

In this paper, 80 Gbps and 100 Gbps OOK data reception using the 14 μm long Si-LPIN GePD are characterized, and clear open eye diagrams at 1550 nm wavelength are demonstrated using 80 Gbps and 100 Gbps on-off keying return-to-zero pseudo-random-bit-sequence data patterns generated using an optical time division multiplexing scheme [17], [18]. As the 14 μm long Si-LPIN GePD is still transit-time limited, the potential performance improvement in terms of responsivity using a 20 μm long Si-LPIN GePD is evaluated. The responsivity is improved to 0.92 A/W at 1550 nm for this 20 μm long Si-LPIN GePD, and similarly clear 80 Gbps and 100 Gbps open eye diagrams at 1550 nm wavelength are demonstrated.

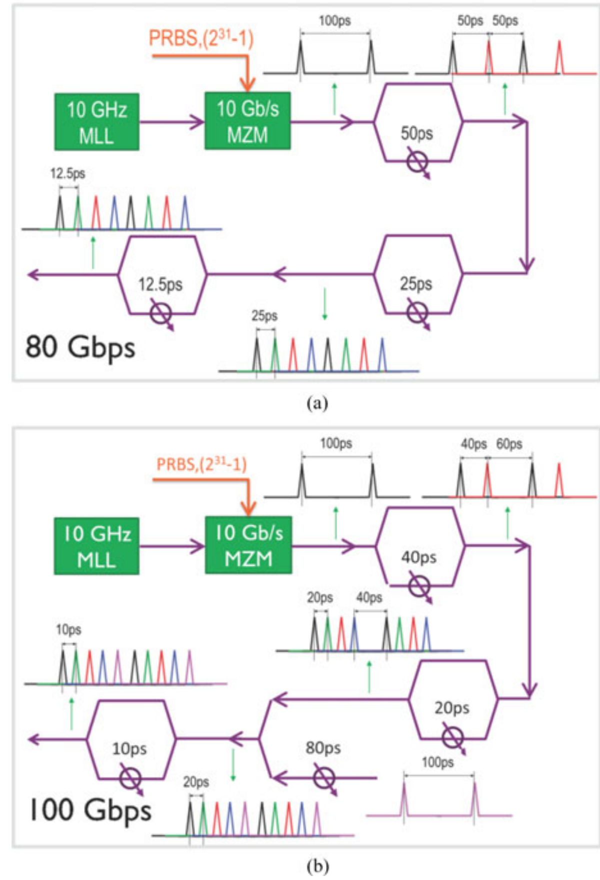


Fig. 4. Schematic diagrams illustrating the experimental set up generating the optical OOK RZ data streams at (a) 80 Gbps and (b) 100 Gbps. MLL: mode-lock laser; MZM: Mach-Zehnder modulator.

II. Device Design and Fabrication

The Si-LPIN GePDs were fabricated in imec's fully integrated Si Photonics Platform along with Si modulators [19] and various passive devices [20]. They go through a process flow described in [21]. Light is coupled from a 220 nm thick single-mode Si waveguide (450 nm wide) to the Ge waveguide using a Si waveguide taper together with a 120 nm thick poly-Si taper (from 150 nm to 250 nm width over a length of 20 μm), as shown in Fig. 1(a). The Ge layer dimensions and doping configuration in the Si-LPIN GePD are shown in Fig. 1(b). The doping distribution in the Si-LPIN GePD is shown in Fig. 2(a), simulated using *Sentaurus Process*.

The electric field distribution in the Si-LPIN GePD at -1 V bias obtained by numerically solving the Poisson's equation using *Sentaurus Device* is shown in Fig. 2(b). In the Ge region, the electric field is stronger than 10^4 V/cm at -1 V, strong enough for photo-generated carriers to drift at their saturation velocity. Therefore, the opto-electrical bandwidth limitation by transit time is minimized. The 14 μm long Si-LPIN GePD exhibits a 3-dB O/E bandwidth of 60 GHz and above (i.e. the RF power delivered by the photodetector to a 50 Ω load drops by a factor of 2 at 60 GHz and above) at 1550 nm as seen in Fig. 3 (reproduced from [16]). Such a high bandwidth should allow 100 Gbps on-off keying data reception as will be discussed in the subsequent sections.

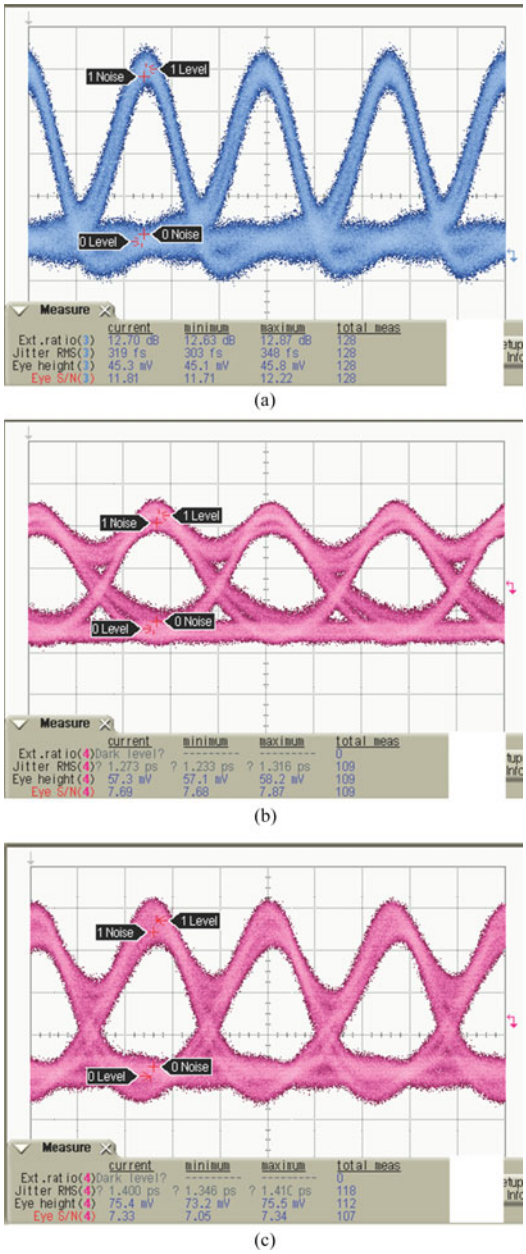


Fig. 5. The 80 Gbps RZ eye diagram measured using (a) a 70 GHz commercial p-i-n photodetector (u2t XPDV 3120R), (b) the 14 μm Si-LPIN GePD at -1 V bias. (c) the 14 μm Si-LPIN GePD at -2 V bias. X scale: 5.0 ps/div, Y scale: 34.8 mV/div. These X&Y scales are for the eyes measured on the Si-LPIN GePD.

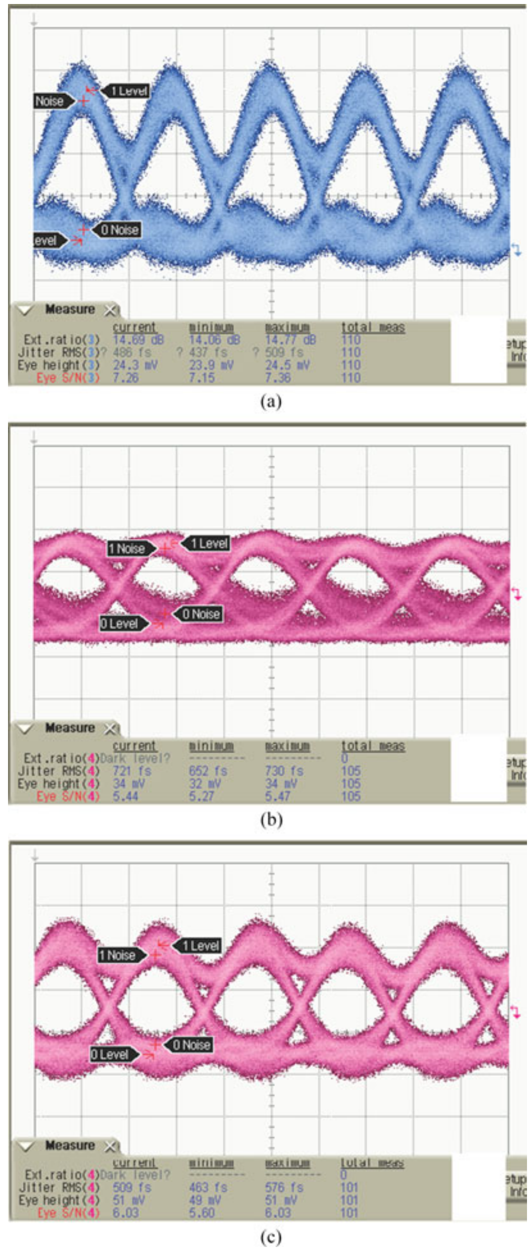


Fig. 6. The 100 Gbps RZ eye diagram measured using (a) a 70 GHz commercial p-i-n photodetector (u2t XPDV 3120R), (b) the 14 μm Si-LPIN GePD at -1 V bias. (c) the 14 μm Si-LPIN GePD at -2 V bias. X scale: 5.0 ps/div, Y scale: 39.4 mV/div. These X&Y scales are for the eyes measured on the Si-LPIN GePD.

III. 80 Gbps and 100 Gbps Data Reception Using a 14 μm Long Si-LPIN GePD

The data reception performance of the 14 μm Si-LPIN GePD was characterized at 1550 nm wavelength using an on-off keying (OOK) return-to-zero (RZ) pseudo-random-bit-sequence (PRBS) data pattern at 80 Gbps and 100 Gbps, respectively. Schematic diagrams illustrating the experimental setup generating the optical OOK RZ data stream at 80 Gbps and 100 Gbps are shown in Fig. 4(a) and (b). Optical pulses from a 10 GHz mode-locked laser (MLL) are on-off keying (OOK) modulated by a commercial Mach-Zehnder modulator at 10 Gbps. The modulated pulses are temporally multiplexed 3 times with delays of 50 ps, 25 ps and 12.5 ps to generate the 80 Gbps data stream. For the 100 Gbps data stream generation, the modulated pulses are firstly multiplexed 2 times with delays of 40 ps and 20 ps. The generated optical pulses are then multiplexed with the original 10 Gbps optical pulses with an 80-ps delay forming a 50 Gbps OOK signal. This is finally multiplexed with a 10-ps delay to create the targeted data rate of 100 Gbps. The OTDM data stream is injected in the silicon waveguide using a C-band fiber-to-chip grating coupler (insertion loss of 2.5 dB). A bias voltage was applied to the Si-LPIN GePD using a 67 GHz *Picoprobe* RF probe with a 50 Ω termination connected to a 65 GHz SHF bias-tee. The electrical output is measured with

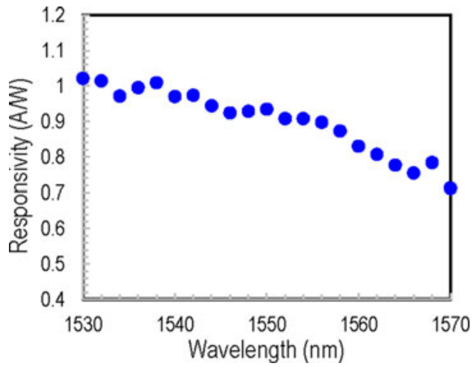
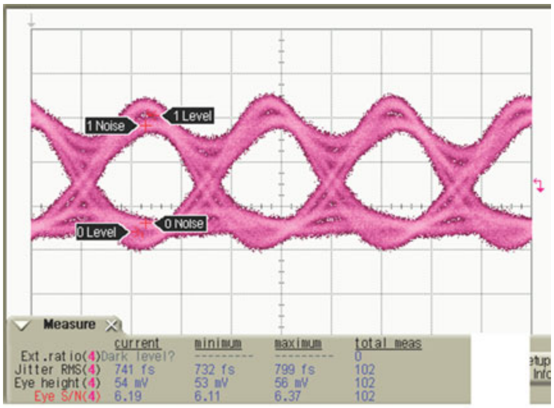
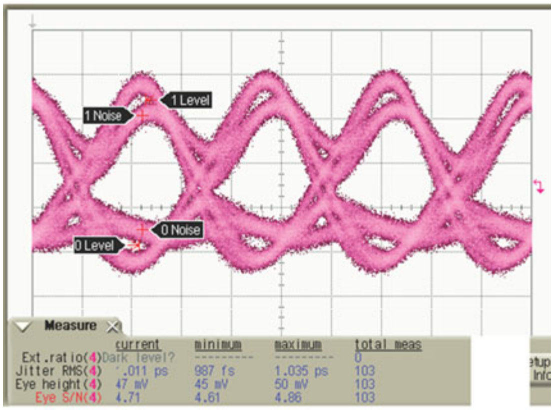


Fig. 7. Responsivity as a function of wavelength for the 20 μm Si-LPIN GePD in the C-band at -1 V bias.



(a)

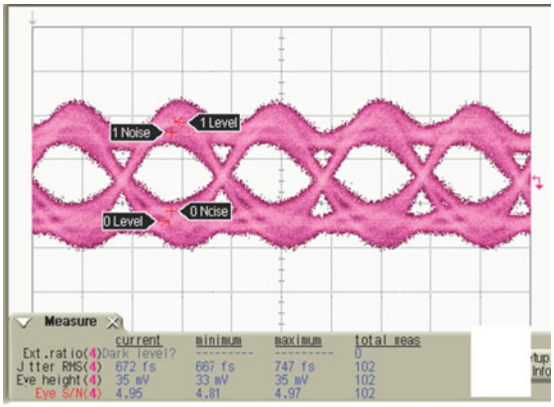


(b)

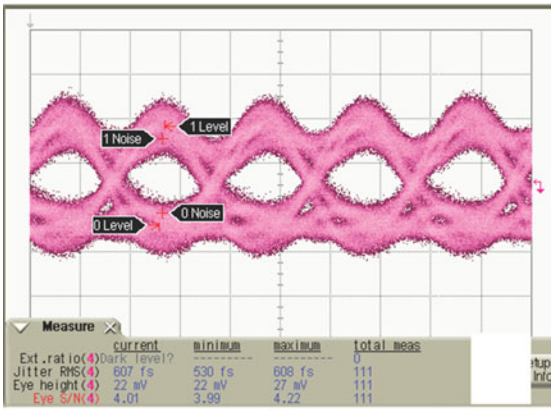
Fig. 8. The 80 Gbps RZ eye diagram measured using (a) the 20 μm Si-LPIN GePD at -1 V bias. (b) the 20 μm Si-LPIN GePD at -2 V bias. X scale: 5.0 ps/div, Y scale: 39.4 mV/div.

an Agilent Infiniium sampling oscilloscope with a 70 GHz remote sampling head plug-in. Given the 50 Ω termination on the probe, the effective responsivity of the photodiode seen by the scope is half of the reported DC responsivity due to the termination resistor being in parallel with the 50 Ω input impedance of the scope.

The reference eye diagram of the 80 Gbps PRBS data pattern measured using a 70 GHz commercial p-i-n photodetector (*u2t XPDV-3120R*) is shown in Fig. 5(a). The extinction ratio of the transmitted data stream is 12.7 dB. The electrical eye diagrams from the Si-LPIN GePD at -1 V and -2 V are shown



(a)



(b)

Fig. 9. The 100 Gbps RZ eye diagram measured using (a) the 20 μm Si-LPIN GePD at -1 V bias. (b) the 20 μm Si-LPIN GePD at -2 V bias. X scale: 5.0 ps/div, Y scale: 39.4 mV/div.

in Fig. 5(b) and (c), respectively. Fig. 6(a-c) show the eye diagrams measured in the 100 Gbps data reception experiment. The extinction ratio of the transmitted data stream is 14.6 dB in this case. The average waveguide-coupled optical power used in both the 80 Gbps and 100 Gbps experiment is 0.62 mW. The corresponding 3-dB O/E bandwidth of the Si-LPIN GePD is $\sim$59 GHz at -1 V as seen in Fig. 3. This explains the bandwidth limitation at -1 V bias especially in the 100 Gbps eye diagram. This bandwidth limitation is overcome by biasing the device at -2 V, where the 14 μm Si-LPIN GePD exhibits a 3-dB O/E bandwidth beyond 67 GHz. It should be mentioned that the eye diagrams of the Si-LPIN GePD are still worse than that of the commercial photodetector, especially at 100 Gbps. As there is a 67 GHz Picoprobe RF probe with a 50-ohm termination, a 65 GHz SHF bias-tee, a 67 GHz RF coaxial-cable and an Agilent Infiniium sampling oscilloscope with a 70 GHz remote sampling head plug-in in the RF link in these on-chip large-signal data reception experiments, it is the frequency response of this RF link that is responsible for the reduced eye diagram quality.

IV. 80 Gbps and 100 Gbps Data Reception Using a 20 μm Long Si-LPIN GePD

The conclusion that the opto-electrical bandwidth of the 14 μm long Si-LPIN GePD is limited by the transit-time and that the responsivity in the C-band (0.74 A/W at 1550 nm) is partly limited by the short device length was drawn in [16]. This indicates that the responsivity of the 14 μm Si-LPIN GePD in the C-band can be improved by increasing the length of the device without compromising on the opto-electrical bandwidth. Therefore, responsivity measurements and 80 Gbps / 100 Gbps data reception experiments were implemented for a 20 μm long Si-LPIN GePD. The responsivity as a function of wavelength in the C-band of a 20 μm long Si-LPIN GePD is shown in Fig. 7. The responsivity at 1550 nm is improved to 0.92 A/W benefiting from this 6 μm device length scaling.

The 80 Gbps and 100 Gbps RZ PRBS data reception experiments at 1550 nm were also implemented for the 20 μm long Si-LPIN GePD. Figs. 8 and 9 show the electrical eye diagrams from the 20 μm Si-LPIN GePD at 80 Gbps and 100 Gbps, respectively. The optical data patterns used in these experiments are the same as those used in the experiments on the 14 μm Si-LPIN GePD. The average waveguide-coupled input optical power used in both the 80 Gbps and 100 Gbps experiment is 0.51 mW in this case. Clear open eye diagrams are again obtained at both data rates. Compared to the 14 μm device, the eye diagrams of the 20 μm device show a slightly slower response, indicating a small reduction of the device bandwidth by scaling the device length to 20 µm. Also more jitter and overshoot can be observed.

V. Conclusion

100 Gbps Ge p-i-n photodetectors without metal contacts on Ge integrated on imec's silicon photonics platform was demonstrated. The high responsivity at 1550 nm of 0.74 A/W and 0.92 A/W for a 14 μm and 20 μm long device respectively and low dark current of 4 nA at -1 V bias make it an attractive component for high bitrate optical transceivers.

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He had been working on high-speed carrier-depletion Mach–Zehnder Si optical modulators. His research interest includes low-power Si photonics optical interconnects. He focused on developing advanced Germanium p-i-n photodetectors and avalanche photodetectors on the imec Si photonics platform, in close collaboration with imec, Belgium.

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